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Engine Oil Fuel Economy Testing - A Tale of Two Tests

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ABSTRACT

Fuel economy is not an absolute attribute, but is highly dependent on the method used to evaluate it. In this work, two test methods are used to evaluate the differences in fuel economy brought about by changes in engine oil viscosity grade and additive chemistry. The two test methods include a chassis dynamometer vehicle test and an engine dynamometer test. The vehicle testing was conducted using the Federal Test Procedure (FTP) testing protocol while the engine dynamometer test uses the proposed American Society for Testing and Materials (ASTM) Sequence VIE fuel economy improvement 1 (FEI1) testing methodology. In an effort to improve agreement between the two testing methods, the same model engine was used in both test methods, the General Motors (GM) 3.6 L V6 (used in the 2012 model year Chevrolet™ Malibu™ engine). Within the lubricant industry, this choice of engine is reinforced because it has been selected for use in the proposed Sequence VIE fuel economy test. Results indicate that agreement between methods does exist for some oils. However in the case of ultra-low viscosity oils and oils containing high levels of friction modifier (FM) additives, the engine dynamometer test gave results much lower than those obtained in the chassis dynamometer testing. The consequence of this is that oils which may significantly improve vehicle fuel economy on the road may not be commercialized since the same benefit is not observed in the engine dynamometer test. Since the chassis dynamometer test uses a complete vehicle, is based on an actual drive cycle, and includes dynamic events such as transient operation and cold start, it is believed to be more representative of actual on-road vehicle performance than the engine dynamometer test. Further, chassis dynamometer testing provides a means to validate the relevance of the proposed Sequence VIE engine test results, including the benefits from highly friction modified and low viscosity oils.

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INTRODUCTION

Fuel economy is inherently difficult to measure with a high degree of precision. This is especially the case when evaluating an engine oil's impact on fuel economy. As a result, many different tests have been developed to investigate friction and fuel economy. Some tests evaluate individual aspects of fuel economy such as friction in specific tribocouples like valve train contacts, power cylinder components, bearings, etc. These types of tests are commonly referred to as bench tests. Other tests measure engine friction by monitoring the torque necessary to spin a non-fired, electric motor-driven, engine. These types of tests are commonly known as Friction Torque Tests (FTTs).

Both bench tests and FTTs have the advantage of being relatively inexpensive and take minimal time to run, however one must be careful not to over-interpret the applicability of results. For example, just because a particular engine oil or chemical additive performs well in a friction, wear, or corrosion bench test, does not guarantee that performance will translate to an actual vehicle. This is a result of the many simplifications and assumptions inherent to the small-scale tests. Because of these simplifications, it is imperative that engine oils and their chemical additives be evaluated in actual fired engines. This is not only the opinion of the authors, but also that of the industry (1, 2, 3, 4), and is further supported by the fact that the industry has made considerable investments in the development of fired engine and vehicle test procedures. For engine oil certification in North America, oils must meet minimum standards in fuel economy improvement (FEI) in the industry standard Sequence VI engine dynamometer test. The Sequence VI test procedure is re-evaluated and updated in conjunction with engine oil category upgrades. At the time of writing this paper, the industry is currently updating this test from the Sequence VID, to the proposed Sequence VIE. The International Lubricant Standardization and Approval Committee (ILSAC) and the American Petroleum Institute (API) have both included minimum performance criteria in this test.

To ensure compliance with greenhouse gas (GHG) emissions and fuel economy standards, the United States Environmental Protection Agency (EPA) and the National Highway Traffic Safety Administration (NHTSA) have adopted vehicle testing standards. These tests utilize complete vehicles on chassis dynamometers to determine emissions and calculate fuel economy. Though there are many standardized and custom drive cycles, two of the most common are the Federal Test Procedure 75 (FTP-75) and Highway Fuel Economy Test (HwFET). For the purposes of this paper, unless otherwise noted, the acronym FTP or Combined FTP testing is defined as the weighted combination of the FTP-75 and HwFET procedures.

The Sequence VI fuel economy test and the FTP testing procedures are designed to be linked, as the test conditions and stage weighting factors of the Sequence VI test were developed to represent conditions experienced during the FTP tests, this work was conducted during the development of the Sequence VID test (5). Engine test conditions from the Sequence VID were carried over to the Sequence VIE test. Therefore, the proposed Sequence VIE test uses the same conditions for evaluation as the Sequence VID but a new engine (the GM 3.6 L Chevrolet™ Malibu™ engine). The objective of this paper is to investigate the similarities and differences between these two procedures, which again, use the same engine. A matrix consisting of five (5) engine oils was developed for testing. The matrix allows for the independent comparison of the impact on fuel economy from lubricant viscosity and from presence and amount of friction modifying additive chemistry.

MECHANICAL TESTS

Two mechanical tests were used to evaluate engine oils' impact on fuel economy, one engine dynamometer test and one chassis dynamometer vehicle test. Engine dynamometer testing was conducted on a 2012 model year, GM, 3.6 L V6 engine using the test conditions from the proposed Sequence VIE fuel economy test. This test consists of several different segments, including fuel economy (FE) evaluations and oil aging periods. FE evaluations are conducted on both candidate and baseline oils. The proposed Sequence VIE baseline oil is an industry-standard oil, which is used to determine the fuel economy improvement (FEI) of the candidate oils. The exact composition of this baseline oil is not known but it is blended to an SAE 20W-30 viscosity grade. Conducting baseline testing before and after the candidate oil evaluations allows for compensation of irreversible hardware drift over the course of the test. Table 1 describes the Sequence VIE test progression, with baseline and candidate oil testing stages. Note: While the proposed Sequence VIE engine test evaluates both fresh and aged oil fuel economy, only fresh oil fuel economy will be discussed in detail. This is because chassis dynamometer testing was conducted on fresh oil only, therefore a comparison between aged oil fuel economy in both tests cannot be made.

Table 1. Sequence VIE Test Progression

Step	Oil	Segment	Data
1	Baseline	FE Evaluation	BLB1
2	Baseline	FE Evaluation	BLB2
3	Candidate	16 hour Aging	-
4	Candidate	FE Evaluation	CA1
5	Candidate	109 hour Aging	-
6	Candidate	FE Evaluation	CA2
7	Baseline	FE Evaluation	BLA

From the data generated in individual FE evaluations, fuel economy improvement is calculated with the following equation 1.

$$FEI1\ (\%) = \frac{(0.8 * BLB2 + 0.2 * BLA) - CA1}{(0.8 * BLB2 + 0.2 * BLA)} * 100 \tag{1}$$

This value represents fresh oil fuel economy. A similar calculation (Equation 2) is used to determine the candidate oil's fuel economy improvement after aging:

$$FEI2\ (\%) = \frac{(0.1 * BLB2 + 0.9 * BLA) - CA2}{(0.1 * BLB2 + 0.9 * BLA)} * 100 \tag{2}$$

The aging period is intended to represent approximately 6500 miles of on-road driving. Thus, the proposed Sequence VIE quantifies both fresh oil and aged oil fuel economy.

Each FE evaluation is composed of a weighted sum of the fuel consumed in each of six discreet speed and load stages. Weighting factors are applied to each stage and were developed to help improve correlation to the FTP testing (5). Test conditions and weighting factors for each test stage can be seen in Table 2.

Table 2. Sequence VIE Fuel Economy Evaluation Stages

Stage	Engine Speed (RPM)	Torque (Nm)	Oil Temp. (°C)	Coolant Temp. (°C)	Weighting Factor
1	2000	105	115	109	0.300
2	2000	105	65	65	0.032
3	1500	105	115	109	0.310
4	695	20	115	109	0.174
5	695	20	35	35	0.011
6	695	40	115	109	0.172

The test conditions were designed to force the engine into various regimes of lubrication including boundary, mixed, and hydrodynamic, while still being reasonable approximations for the speeds and loads experienced in the FTP-75 and HwFET tests. It is important to note that each tribocouple within the engine may operate in a different regime of lubrication at any particular condition set. Gross simplifications are made by describing certain condition sets as boundary or hydrodynamic. In this manner, assignment of a macroscopic lubrication regime is much more qualitative than quantitative. A detailed discussion of lubrication regimes is beyond the scope of this paper, but one good resource is (6).

In this study, chassis dynamometer testing was conducted with the FTP-75 and HwFET driving schedules. Plots of these driving schedules can be seen in Figures 1 and 2. To improve test precision, many improvements were made to the standard test procedure, including a robotic driver, dedicated dynamometer tires, laser vehicle alignment and more. A full explanation of these improvements can be obtained in previous publications (7, 8). Fuel economy was calculated using the carbon balance method as described in (9). The FTP-75 procedure consists of three phases. Fuel economy and emissions are evaluated independently for each phase. A weighted average is then used to calculate total cycle fuel economy (9). The HwFET consists of only one phase and represents highway driving.

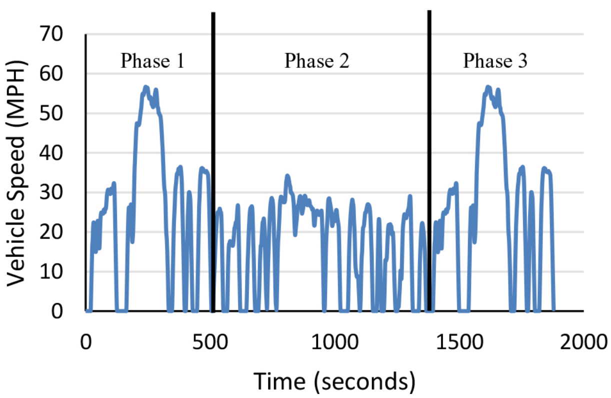

Figure 1. FTP-75 Driving Schedule

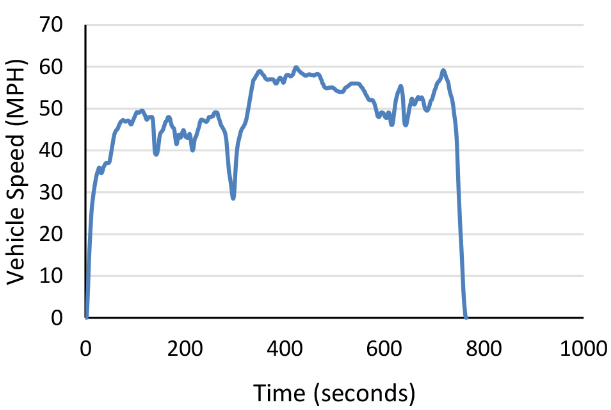

Figure 2. HwFET Driving Schedule

The vehicle used for testing was the 2012 model year Chevrolet™ Malibu™, powered by GM's 3.6 L, port fuel injected, V6 engine. This vehicle was specifically chosen as it is the same model engine used in the proposed Sequence VIE test. The authors believe that use of the same hardware for both engine dynamometer and chassis dynamometer testing will increase chances of agreement between the two methods. To generate enough data for statistical robustness, all FTP testing was conducted in triplicate, with the exception of the GF-5 Baseline oil that was evaluated in triplicate, twice for a total of 6 tests.

TEST OILS

Test oils were carefully developed to represent relevant formulations and isolate the two variables being studied, oil viscosity and additive chemistry. Indeed, each oil uses the same Group III oil base stocks, same viscosity modifier (VM) type, and same base additive package. To achieve different viscometrics, different viscosity base stocks and VM treat rates were used. To minimize variability, all base stock cuts came from the same oil slate. Additionally, while the VM treat rate was altered for each viscosity grade, the VM type was held constant. Similarly, the exact same additive package was used for each oil, with the exception of the friction modification chemistry used to evaluate FM as a variable. This careful approach to test oil formulation was done to minimize any potential confounding. The additive package used for all oils was based on an ILSAC GF-5 licensed product. More information about the test oils can be seen in Table 3.

Table 3. Test Oils

Test Oil	Description	SAE Grade	D4683 HTHS Viscosity (cP)	FM
1	GF-5 Baseline	5W-30	3.1	Standard
2	High Viscosity	10W-40	3.7	None
3	Mid Viscosity	5W-30	3.1	None
4	Low Viscosity	0W-16	2.3	None
5	Mid Viscosity + High FM	5W-30	3.1	High

The two variables studied are oil viscosity and friction modifier presence and treat rate. In this manner, differences in fuel economy can be isolated as a function of viscosity or friction modification, or considered together. A graphic which represents each test oil can be seen in Figure 3.

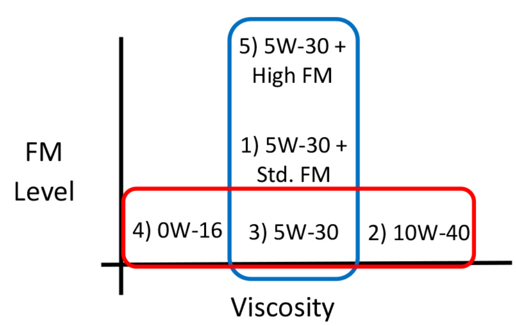

Figure 3. Test Oil Graphic

RESULTS

The results from the proposed Sequence VIE fuel economy test can be seen in Table 4. This table includes both fresh oil fuel economy (FEI1) and aged fuel economy (FEI2).

Table 4. Sequence VIE Data

Test Oil	Description	SAE Grade	FEI1 (%)	FEI2 (%)	FEI Sum (%)
1	GF-5 Baseline	5W-30	1.98	1.24	3.22
2	High Viscosity	10W-40	1.10	1.08	2.18
3	Mid Viscosity	5W-30	1.35	1.09	2.45
4	Low Viscosity	0W-16	1.26	1.31	2.58
5	Mid Viscosity + High FM	5W-30	1.96	1.76	3.72

Results have been adjusted with the engine hours correction factor, recently established from the Sequence VIE precision matrix (as of Summer 2016) and can be seen in Figure 4. At the time of writing, no other severity adjustments were established and were thus not applied. The equations used to determine the engine hour correction factor can be seen in the Appendix, section 1.0.

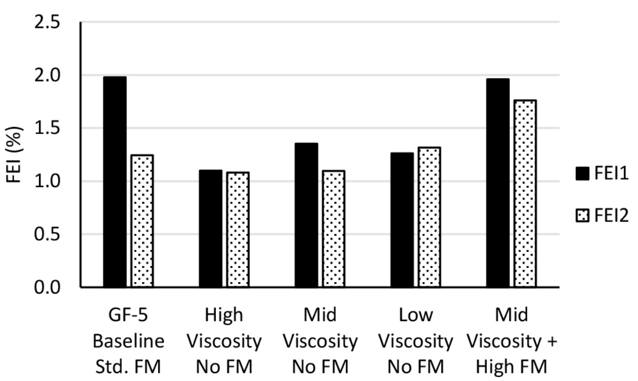

Figure 4. Sequence VIE Data

Table 5. FTP Data

Test Oil	Description	SAE Grade	FTP Avg. (mpg)	HwFET (mpg)	Combined (mpg)
1	GF-5 Baseline	5W-30	21.00	36.17	25.89
2	High Viscosity	10W-40	20.79	35.94	25.66
3	Mid Viscosity	5W-30	20.92	36.06	25.79
4	Low Viscosity	0W-16	21.17	36.27	26.05
5	Mid Viscosity + High FM	5W-30	21.09	36.37	26.01

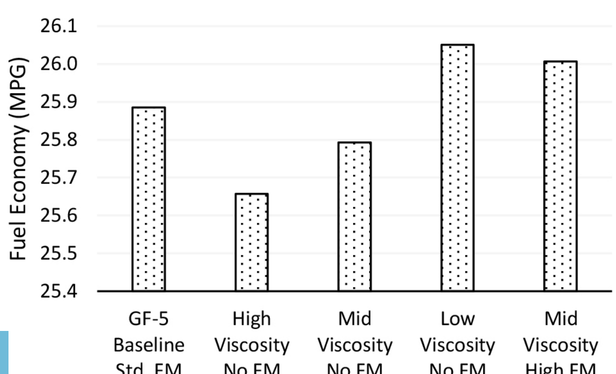

Figure 5. Combined Fuel Economy FTP Data

The chassis dynamometer data is presented as FTP-75 weighted average, HwFET, and Combined Average. These results can be seen in tabular form in Table 5 and graphical form in Figure 5.

RESULTS ANALYSIS

FEI1 data from the proposed Sequence VIE (Figure 4) tests shows two levels of performance. Although there are subtle differences between viscosity grades, the largest difference seems to be between friction modified and un-friction modified oils. Interestingly, the 0W-16's FEI1 performance is lower than that of the 5W-30. This indicates that the 0W-16 may simply be too thin for this particular engine operating under these operating conditions. Indeed, this trend has been observed by the industry and has resulted in the development of an additional test, the proposed Sequence VIF. The intention is to use this test to evaluate XW-16 lubricants (GF-6B), while the proposed Sequence VIE will be retained for the evaluation of traditional viscosity grades (GF-6A). Additionally, there is no discernable benefit in fresh oil fuel economy (FEI1) between the standard and high FM levels. FEI2, however, responds very well to the high FM level, resulting in the highest FEI2 and FEI Sum.

Data from the FTP testing suggests this test may offer more resolution than the proposed Sequence VIE test. Examining the three oils without FM, the FTP data indicates a clear improvement in fuel economy when moving from the highest viscosity grade to the lowest viscosity grade. Additionally, the test responds to level of FM. In the case of the 5W-30s, the addition of the standard FM treat rate improves fuel economy by approximately 0.1 mpg. The addition of the high treat rate of FM improves the fuel economy an additional 0.1 MPG. The addition of this elevated FM increases the fuel economy 0.2 mpg over the 5W-30 containing no FM. A statistical analysis was conducted on the FTP data which determined differences in Combined fuel economy were statistically significant (on a 95% confidence interval) between all oils with the exception of the 0W-16 and 5W-30 with High FM. This indicates that the 5W-30 with High FM offers the same level of fuel economy performance as the 0W-16. Statistical analysis of the FTP results can be seen in the Appendix, section 1.1.

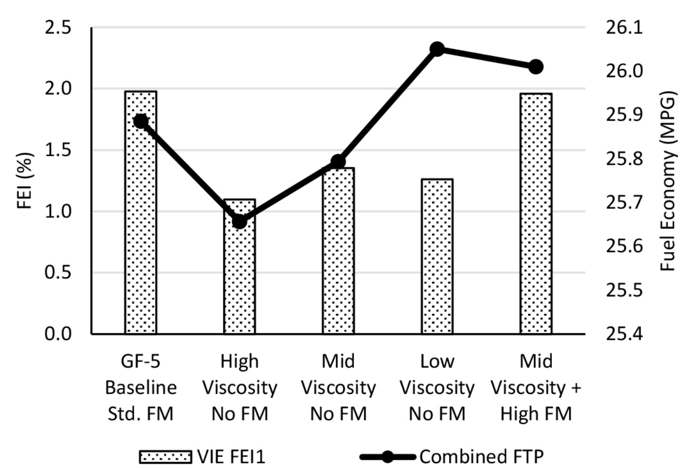

Figure 6. FEI1 and FTP Data

While much information can be gained by reviewing the results of each tests separately, even more can be gained with a direct comparison. Figure 6 shows both proposed Sequence VIE and Combined FTP data in one graphic.

Figure 6 highlights the divergence of results between the two test methods. Relative to the FTP, the proposed Sequence VIE gives lower fuel economy improvement results from the low viscosity, 0W-16 engine oil. Additionally, the proposed Sequence VIE shows no improvement in fresh oil fuel economy (FEI1) between the GF-5 Baseline (5W-30 with standard FM) and the Mid Viscosity + High FM oil, while the Combined FTP testing shows a clear increase.

To better understand the impact of engine operating conditions on final results, it is helpful to examine each stage individually. Figure 7 shows FEI1s for each individual test stage in the proposed Sequence VIE on the three oils without FM. Stages are arranged in order of predicted lubrication regime, starting with the stages closest to the boundary lubrication regime on the left and working toward the most hydrodynamic stage on the right. For this analysis, no weighting factors are included, only the engine hours correction factor.

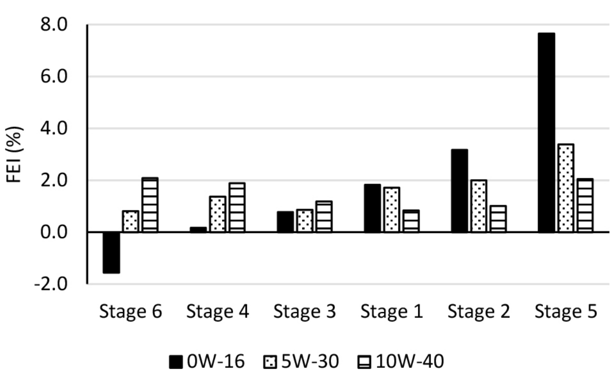

Figure 7. FEI1 Data by Test Stage

It is clear that the benefit of the low viscosity lubricants occurs in the more-hydrodynamic lubrication stages 1, 2, and 5. Conversely, the high loads, high temperatures, and low speeds of stage 6 and 4, more-boundary lubrication conditions exist, and the result is a detriment to performance with the 0W-16. A similar analysis can be performed with the 5W-30 oils. Figure 8 shows the FEI1s for the three 5W-30 oils with varying FM treat rates.

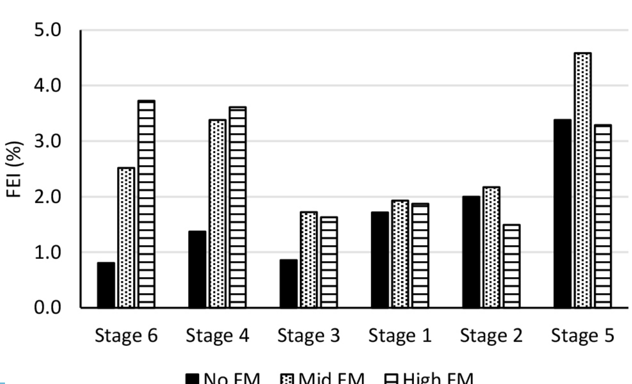

Figure 8. FEI1 Data by Test Stage (5W-30s only)

In this case, it is apparent that the higher FM concentration is most beneficial in stages 6 and 4. This is consistent with the understanding that FMs reduce friction in the boundary lubrication regime. Interestingly, this oil also shows a debit in performance in stages 2 and 5. It is unclear whether this difference is real or a result of no severity correction factor being available (the 5W-30 + High FM was the only oil evaluated in a different engine, all other oils were evaluated in a single engine), or a result of some other, undetermined cause.

Additionally, the chassis dynamometer testing data can also be reviewed by test phase to help understand the impact of test conditions on fuel economy performance. Figure 9 shows fuel economy improvement between the GF-5 baseline oil and each of the others. Please note that for this analysis, the GF-5 oil provides the baseline, which is a completely different oil from the homologated SAE 20W-30 used in the Sequence VIE testing. While use of the Sequence VIE baseline oil in the FTP test would have created a direct comparison, rules for the use of the Sequence VIE baseline oil preclude its use for anything other than Sequence VIE testing.

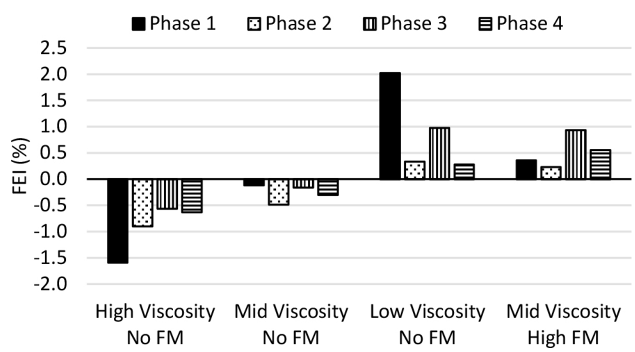

Figure 9. Fuel Economy Improvement by Phase

Reviewing the data in this manner, together with engine oil temperature data provided in Table 6, helps explain the source of the fuel economy improvements.

Table 6. Oil Temperatures during FTP Testing

FTP Phase	Description	Max.	Avg.
Phase 1	Cold Start City	66.7	42.8
Phase 2	Transient	101.3	88.7
Phase 3	Hot Start City	104.8	100.3
Phase 4	HwFET	107.5	106.4

During the first phase, the engine and oil are cool and the viscosity of the oil has the largest impact on fuel economy. Here the 10W-40 is the worst performing oil and the 0W-16 is the best performing oil. As testing continues and the engine oil becomes warm, the difference in viscosity becomes less pronounced. Comparison of results in Phases 2 and 3 between the low viscosity oil and the high FM containing 5W-30 show very similar performance. In the fourth and final phase, engine oil temperature is the highest, engine loads are also high. In this phase, the high FM containing 5W-30 actually performs better than the 0W-16. It is theorized that, in this phase, the boundary lubrication regime is experienced in more tribocouples (or for greater proportions of time) with the 0W-16 than the 5W-30. This is likely a result of the 0W-16's reduced oil film thickness. Additionally, the friction modifier in the 5W-30 helps to reduce friction where the boundary lubrication regime does occur.

In both engine dynamometer and chassis dynamometer testing, fuel economy performance was highly dependent upon test conditions. Under some conditions, reduction of engine oil viscosity resulted in the best fuel economy. In others, FM content provided the largest improvement. Additional work should be conducted to maximize fuel economy through the optimization of both viscosity and additive chemistry.

SUMMARY AND CONCLUSIONS

In this paper, five test oils were prepared and evaluated in the proposed Sequence VIE engine test and the FTP-75 + HwFET chassis dynamometer tests. Efforts were taken to improve agreement between the two testing methodologies by the use of consistent hardware. From the data generated, the following conclusions can be made:

- Relative to the FTP data, the proposed Sequence VIE test gives lower fresh oil fuel economy improvement results for the low viscosity (0W-16) engine oil - this has already been addressed by the industry with the creation of the proposed Sequence VIF test.
- Relative to the FTP data, the proposed Sequence VIE test gives lower fresh oil fuel economy improvement results for the highly friction-modified oil. This has not been addressed by the industry.
- The vehicle FTP testing data indicate that a highly friction modified 5W-30 can match the fuel economy performance of a 0W-16.
- The vehicle FTP testing data show a statistically significant fuel economy improvement of 0.47% between the highly friction modified oil and the GF-5 baseline oil. This represents a theoretical annual reduction of 4.91 million metric tons of CO_2 across all light duty vehicles in the U.S.A. (10).

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DEFINITIONS/ABBREVIATIONS

CAFE - Corporate average fuel economy

FE - Fuel economy

FEI - Fuel economy improvement

FM - Friction modifier

FTP - Federal Test Procedure - FTP consists of two cycles (FTP-75 & HwFET)

FTP-75 - Chassis dynamometer test procedure consisting of three testing phases

HTHS - High Temperature High Shear

HwFET - Highway Fuel Economy Test

ILSAC - International Lubricants Standardization and Approval Committee

mpg - Miles per gallon (US Customary gallon)

mph - Miles per hour

NHTSA - National Highway Traffic Safety Administration

VM - Viscosity modifier

APPENDIX

1.0. CALCULATIONS FOR HOUR CORRECTION FACTOR

FEI1 = 0.000518 x (Engine hr. @ EOT-675) + FEI1_Original
FEI2 = 0.000381 x (Engine hr. @ EOT-675) + FEI2_Original

Statistical Analysis of FTP Data

1.1. Summary Statistics for Combined Fuel Economy (MPG)

Test Oil	Count	Average	Median	Variance	Standard deviation	Minimum	Maximum	Skewness
1	6	25.8833	25.89	0.002387	0.048854	25.81	25.94	-0.47228
2	3	25.66	25.64	0.0028	0.052915	25.62	25.72	1.45786
3	3	25.7933	25.78	0.001033	0.032146	25.77	25.83	1.54539
4	3	26.0467	26.05	0.000233	0.015275	26.03	26.06	-0.93522
5	3	26.0067	26.01	0.000633	0.025166	25.98	26.03	-0.58558
Total	18	25.8789	25.89	0.018858	0.137323	25.62	26.06	-0.41541

Since there was a large difference between the maximum and minimum standard deviation, a variance check was also performed, to ensure the assumptions for ANOVA were met:

1.2. Variance Check

	Test	P-Value
Bartlett	3.21938	0.521806

Comparison	Sigma1	Sigma2	F-Ratio	P-Value
1-2	0.048854	0.052915	0.852381	0.7643
1-3	0.048854	0.0321455	2.30968	0.6584
1-4	0.048854	0.0152753	10.2286	0.1829
1-5	0.048854	0.0251661	3.76842	0.4458
2-3	0.052915	0.0321455	2.70968	0.5391
2-4	0.052915	0.0152753	12	0.1538
2-5	0.052915	0.0251661	4.42105	0.3689
3-4	0.032146	0.0152753	4.42857	0.3684
3-5	0.032146	0.0251661	1.63158	0.76
4-5	0.015275	0.0251661	0.368421	0.5385

Since the P-value is greater than 0.05, there is not a statistically significant difference between the standard deviations at the 95% confidence level. This validates a key assumption of ANOVA.

1.3. ANOVA

ANOVA Table for Combined FE by Test Oil

Source	Sum of Squares	Df	Mean Square	F-Ratio	P-Value
Between groups	0.299244	4	0.074811	45.59	0.00
Within groups	0.0213333	13	0.001641		
Total (Corr.)	0.320578	17			

Since the P-value of the F-test is less than 0.05, there is a statistically significant difference between the means of the five test oils. Range test will determine which are significant.

1.4. Statistical Significance, Multiple Range Test for Combined FE by Test Oil, by Duncan at 95%

Test Oil	Count	Mean	Homogeneous Groups
2	3	25.66	X
3	3	25.7933	X
1	6	25.8833	X
5	3	26.0067	X
4	3	26.0467	X

Contrast	Sig.	Difference
1-2	*	0.223333
1-3	*	0.09
1-4	*	-0.163333
1-5	*	-0.123333
2-3	*	-0.133333
2-4	*	-0.386667
2-5	*	-0.346667
3-4	*	-0.253333
3-5	*	-0.213333
4-5		0.04

* indicates a statistically significant difference.

This tests indicates that there is a statistically significant difference between means of all test oils, with the exception of test oils 4 and 5, which are the 0W-16 and 5W-30 with high FM.

Test Oil	Description	HTHS
1	Baseline Std. FM	3.1
2	High Viscosity No FM	3.7
3	Mid Viscosity No FM	3.1
4	Low Viscosity No FM	2.3
5	Mid Viscosity High FM	3.1